Chiral symmetry restoration and strong CP violation in a strong magnetic background

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Based on work done with Ana Júlia Mizher:

Chiral transition in a strong magnetic background.
Phys.Rev.D78:025016,2008.
arXiv:0804.1452 [hep-ph]

Can a strong magnetic background modify the nature of the chiral transition in QCD?
Nucl.Phys.A820:103C-106C,2009.
arXiv:0810.3693 [hep-ph]

CP Violation in the Linear Sigma Model.
Nucl.Phys.A820:247-250,2009.
arXiv:0810.4115 [hep-ph]

CP violation and chiral symmetry restoration in the hot linear sigma model in a strong magnetic background.
arXiv:0810.5162 [hep-ph]

Work in progress with: M. Chernodub, K. Fukushima, A.J. Mizher (χ & deconf. transitions)
G. Denicol, T. Kodama, A.J. Mizher (effects on diffusion & hydro)

Motivation

- Topologically nontrivial configurations of the gauge fields allow for a CP-violating term in the Lagrangian of QCD

$$\boxed{\mathcal{L}_\theta = -\frac{\theta}{32\pi^2} g^2 F^{\mu\nu a} \tilde{F}^a_{\mu\nu}}$$

However, experiments indicate $\theta < 10^{-10}$.

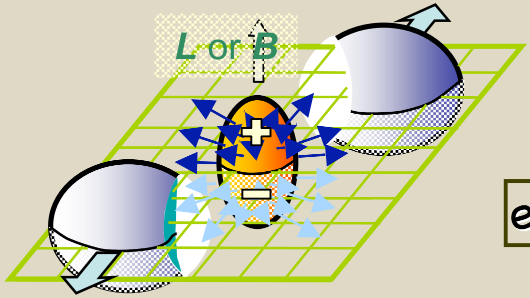
- Spontaneous breaking of P and CP are forbidden in the true vacuum of QCD for $\theta=0$ [Vafa & Witten (1984)]. However, this does not hold at finite temperature [Bronoff & Korthals Altes; Azcoiti & Galante; Cohen,…] and metastable states are allowed -> chance to probe the topological structure of QCD !

- Metastable P- and CP-odd domains could be produced in heavy ion collisions [Kharzeev, Pisarski & Tytgat (1998)]. Simulations of topological charge distribution (Chern-Simons # fluctuations) [Kharzeev, Krasnitz & Venugopalan (2002)].

- Signature? Mechanism based on the separation of charge -> the chiral magnetic effect [Kharzeev (2006); Kharzeev & Zhitnitsky (2007); Kharzeev, McLerran & Warringa (2008); Fukushima, Kharzeev & Warringa (2008)] under very strong magnetic fields in non-central collisions; sensitive experimental observable [Voloshin (2000,2004)]

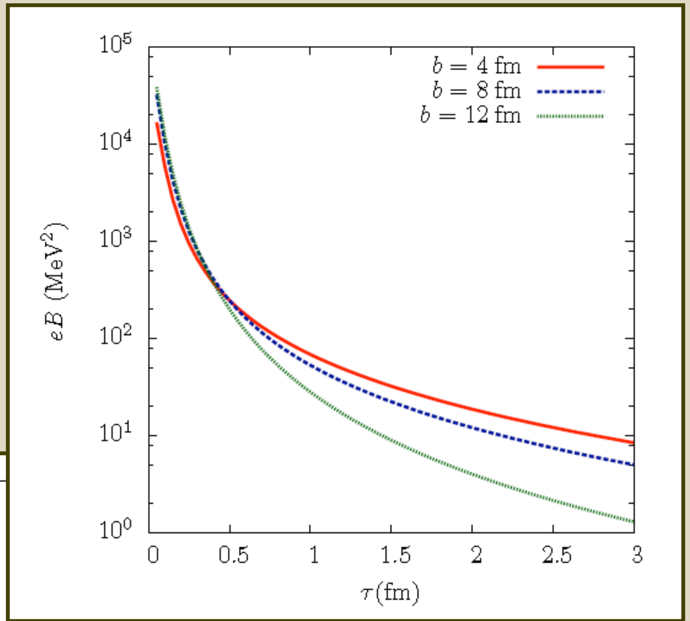
❖ High magnetic fields in non-central RHIC collisions

[Kharzeev, McLerran & Warringa (2008)]

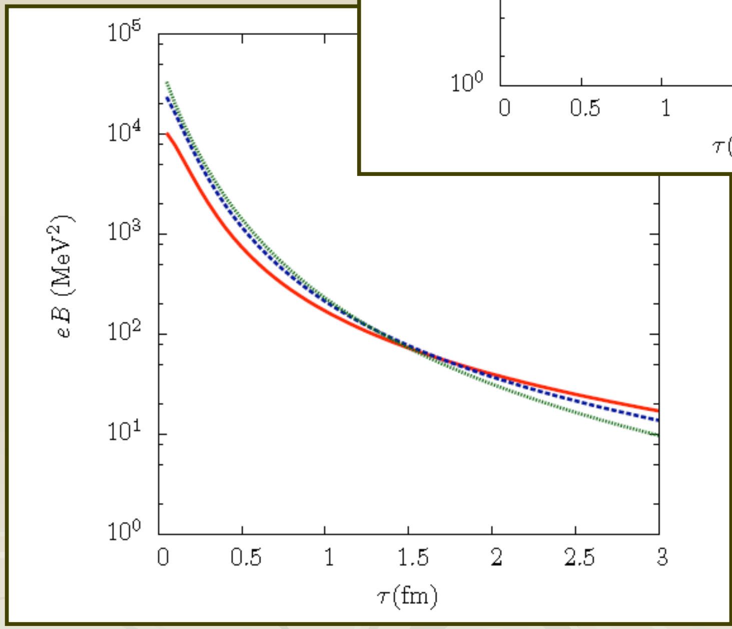


[Voloshin, QM2009]

$eB \sim 10^4$–10^5 MeV^2 $\sim 10^{19}$ G



[Au-Au, 200 GeV]



[Au-Au, 62 GeV]

For comparison:

- "Magnetars": B ~ 10^{14}–10^{15} G at the surface, higher in the core [Duncan & Thompson (1992/1993)]
- Early universe (relevant for nucleosynthesis): B~ 10^{24} G for the EWPT epoch [Grasso & Rubinstein (2001)]

❖ CP violation in heavy ion collisions

- Rate of *instanton* transitions at zero temperature (tunneling) ['t Hooft (1976)]:

(no quarks) $$\boxed{\frac{dN_t^{\pm}}{d^3x\,dt\,d\rho} = 0.0015\left(\frac{2\pi}{\alpha_s}\right)^6 e^{-2\pi/\alpha_s}\frac{1}{\rho^5}}$$ $$\boxed{Q_w = \pm 1}$$

- High T tends to decrease this rate [Pisarski & Yaffe (1980)], but allows for *sphaleron* transitions (rate <u>increases</u> with T). For Yang-Mills [Moore et al. (1998); Bodeker et al. (2000)]:

$$\boxed{\frac{dN_t^{\pm}}{d^3x\,dt} \sim 25.4\ \alpha_w^5 T^4}$$

- Estimate for QCD via N_c scaling [Kharzeev et al (2008)]:

$$\boxed{\frac{dN_t^{\pm}}{d^3x\,dt} \sim 192.8\ \alpha_s^5 T^4}$$

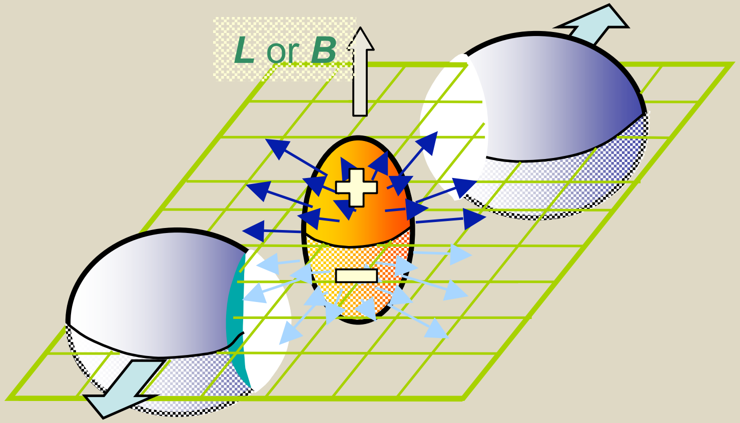
- Due to the anomaly the Ward identities are modified, and the charges Q_L and Q_R obey the following relations (for $N_+=N_-$ at $t \to -\infty$):

$$\boxed{(N_L - N_R)_{t\to\infty} = 2N_f Q_w}$$ $$\boxed{N_L - N_R = \int d^4x\,(Q_L - Q_R) = -\int d^4x\,Q_5}$$

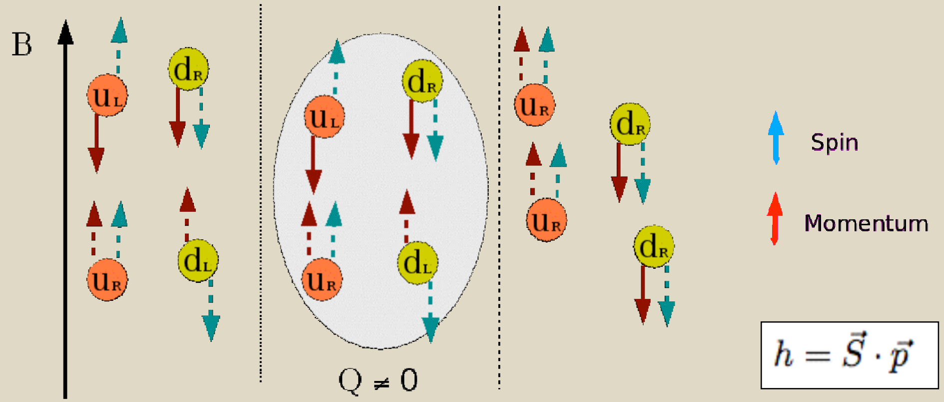
so that fermions interacting with non-trivial gauge fields ($Q_w \neq 0$) have their chirality changed!

❖ Chiral magnetic effect

In non-central heavy ion collisions a strong magnetic field is generated in the orbital angular momentum direction (perpendicular to the reaction plane) and there can be regions with $Q_w \neq 0$ (inducing *sphaleron* transitions):



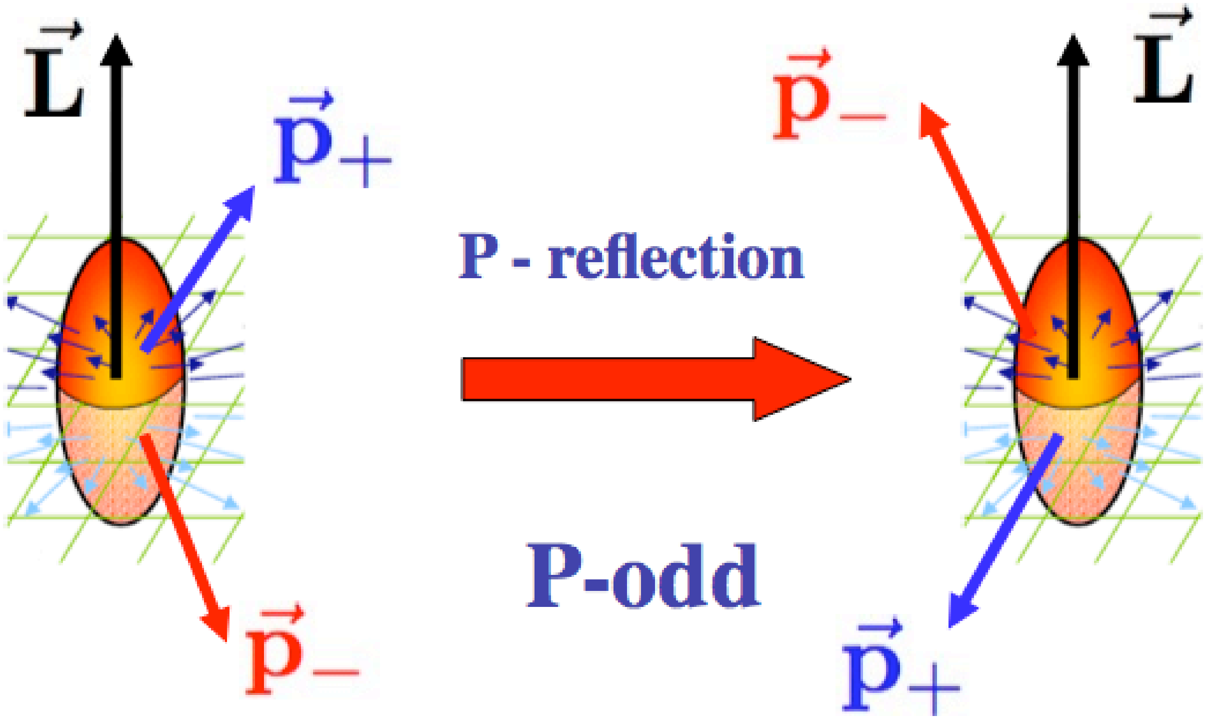
[Voloshin, QM2009]



[Kharzeev, McLerran & Warringa (2008)]

- The strong B field restricts quarks (all in the lowest Landau level, aligned with B) to move along its direction
- Q_w=-1, e.g., converts L -> R: inversion of the direction of momentum
- Net current and charge difference created along the B direction

Charge separation = parity violation:



$$\mathbf{P}: \quad \vec{p} \rightarrow -\vec{p}; \quad \vec{L} = \vec{r} \times \vec{p} \rightarrow \vec{L}$$

[Kharzeev, QM2009]

Several theoretical/phenomenological questions arise:

- How does the QCD phase diagram looks like including a nonzero uniform B ? (another interesting "control parameter" ?)

- Where are the possible metastable CP-odd states and how "stable" they are? What are their lifetimes ?

- Are there modifications in the nature of the phase transitions ?

- Are the relevant time scales for phase conversion affected ?

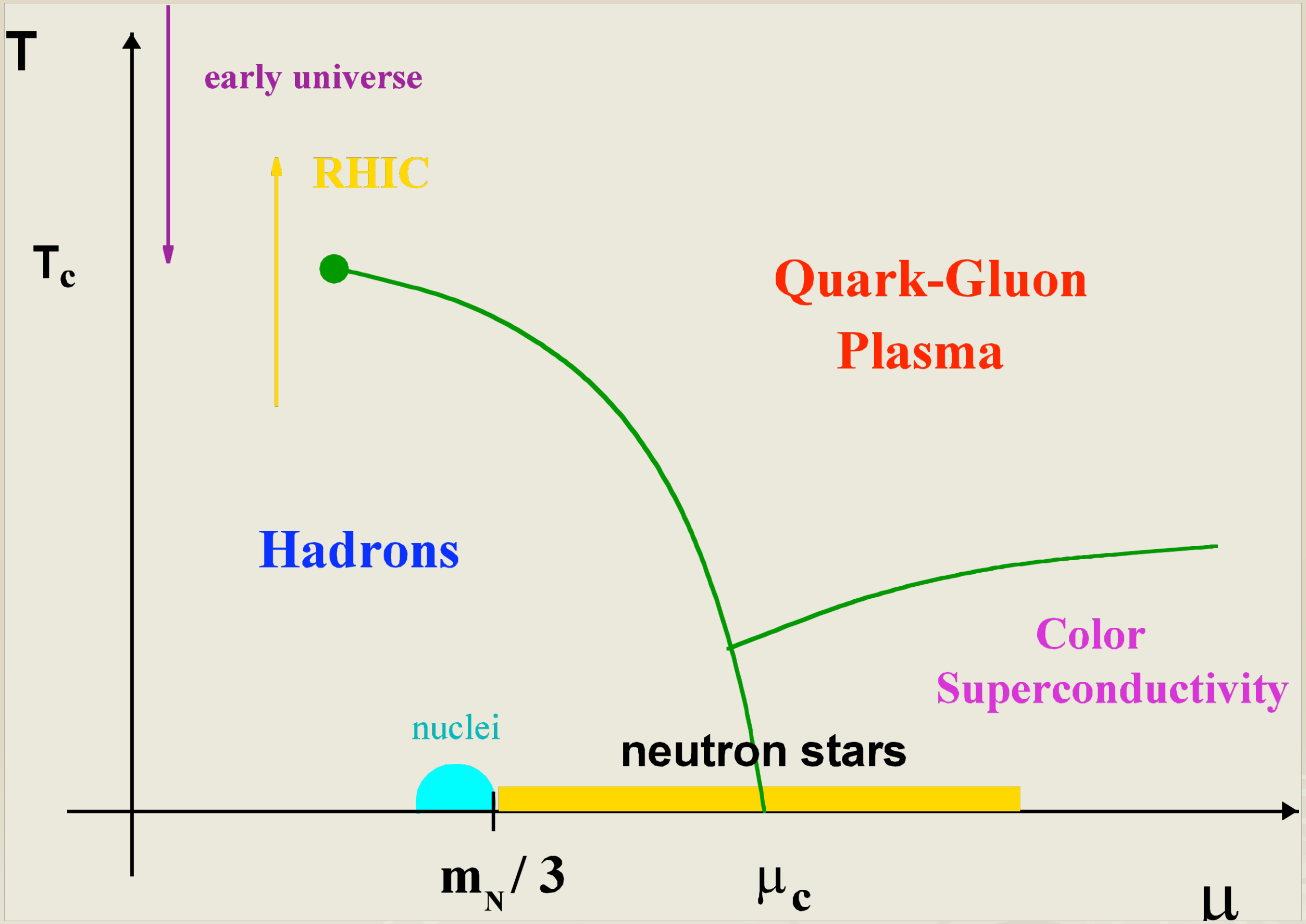
- Are there other new phenomena (besides the chiral magnetic effect) ?

- What is affected in the plasma formed in heavy ion collisions ?

- Which are the good observables to look at ? Can we investigate it experimentally ? Can we simulate it on the lattice ?

Here, we consider effects of a strong magnetic background and CP violation on the chiral transition at finite temperature in an effective model for QCD

Pictorially, two basic questions (2 steps in this talk):



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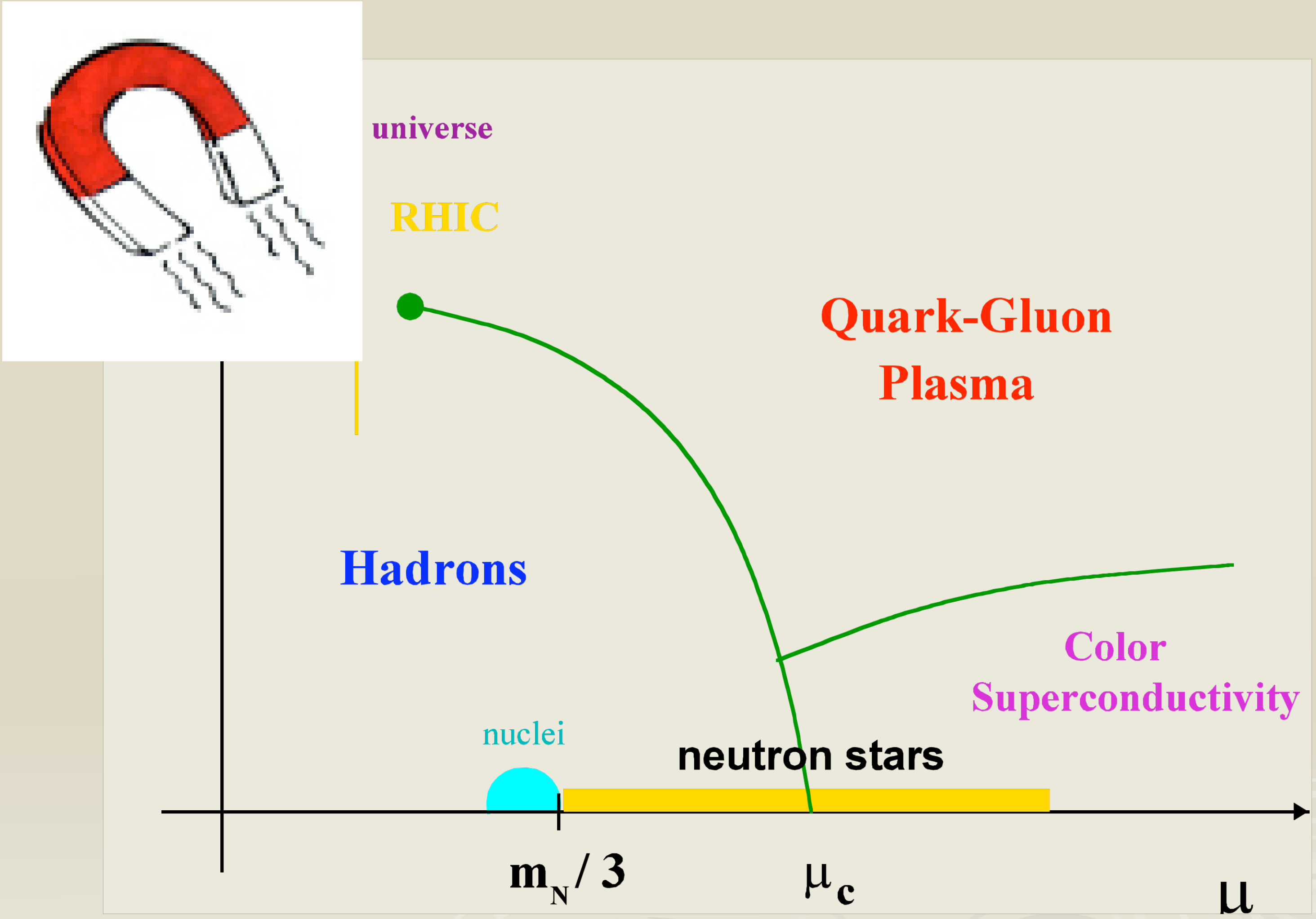

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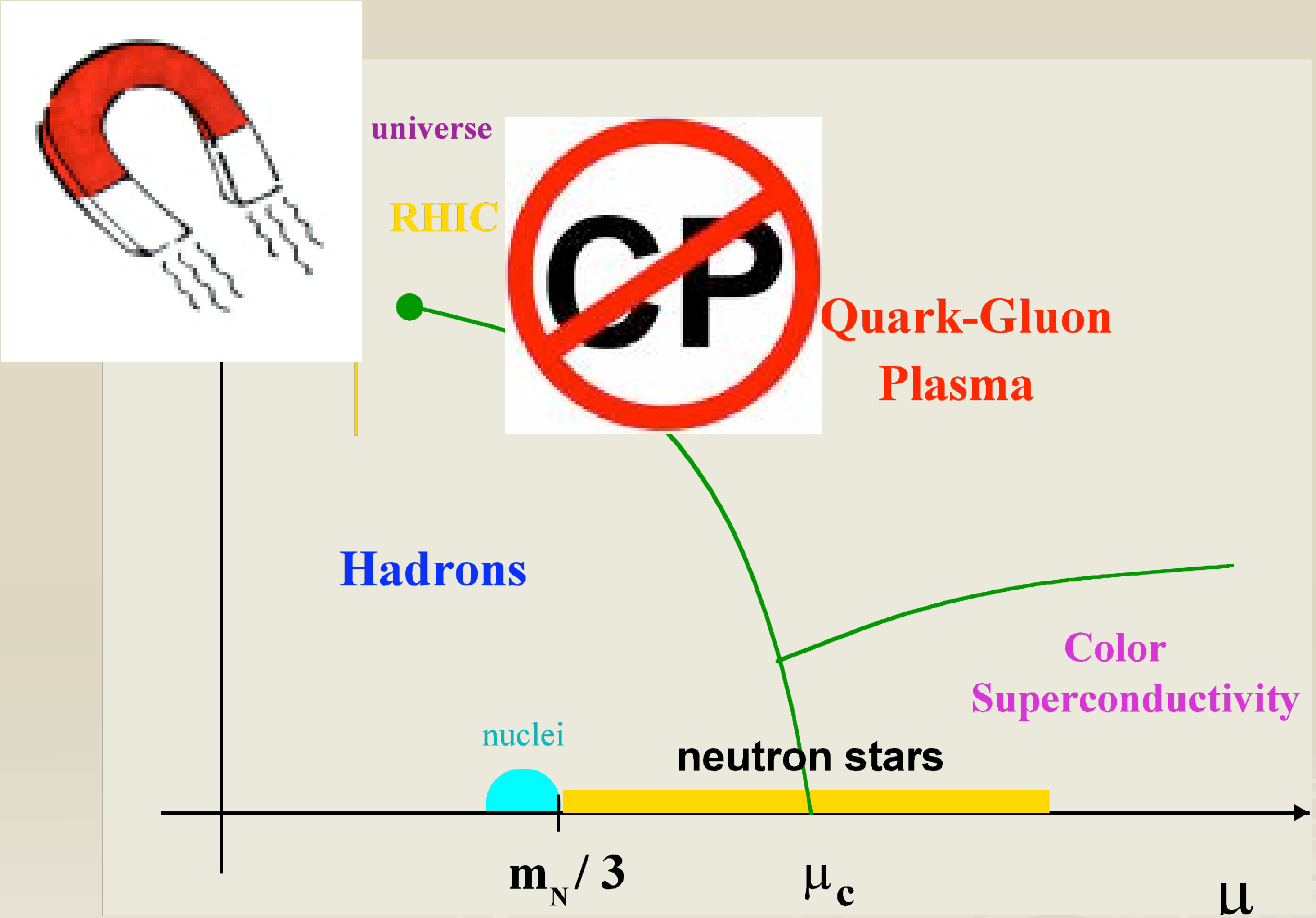

Effective theory for the chiral transition (LσM)

[Gell-Mann & Levy (1960); Scavenius, Mócsy, Mishustin & Rischke (2001); ...]

- Symmetry: for massless QCD, the action is invariant under $SU(N_f)_L \times SU(N_f)_R$
- "Fast" degrees of freedom: quarks
  "Slow" degrees of freedom: mesons
- Typical energy scale: hundred of MeV
- We choose $SU(N_f=2)$, for simplicity: we have pions and the sigma
- Framework: coarse-grained Landau-Ginzburg effective potential
- $SU(2) \times SU(2)$ spontaneously broken in the vacuum
- Also accommodates explicit breaking by massive quarks
- All parameters chosen to reproduce the vacuum features of mesons

Step 1: incorporating a strong magnetic background

[Mizher & ESF (2008,2009)]

Assume the system in the presence of a strong magnetic field background that is constant and homogeneous and compute the effective potential.

Quarks constitute a thermalized gas that provides a background in which the long wavelength modes of the chiral condensate evolve. Hence:

At $T = 0$ (vacuum: χ symm. broken; reproduce usual LσM & χPT results)

- Quark d.o.f. are absent (excited only for $T > 0$)
- The σ is heavy ($M_\sigma \sim 600$ MeV) and treated classically
- Pions are light: fluctuations in π^+ and π^- couple to B; fluctuations in π^0 give a B-independent contribution

At T > 0 (plasma: χ symm. approximately restored)

- Quarks are relevant (fast) degrees of freedom: incorporate their thermal fluctuations in the effective potential for σ (integrate over quarks)

- Pions become rapidly heavy only after T_c, so we incorporate their thermal contribution

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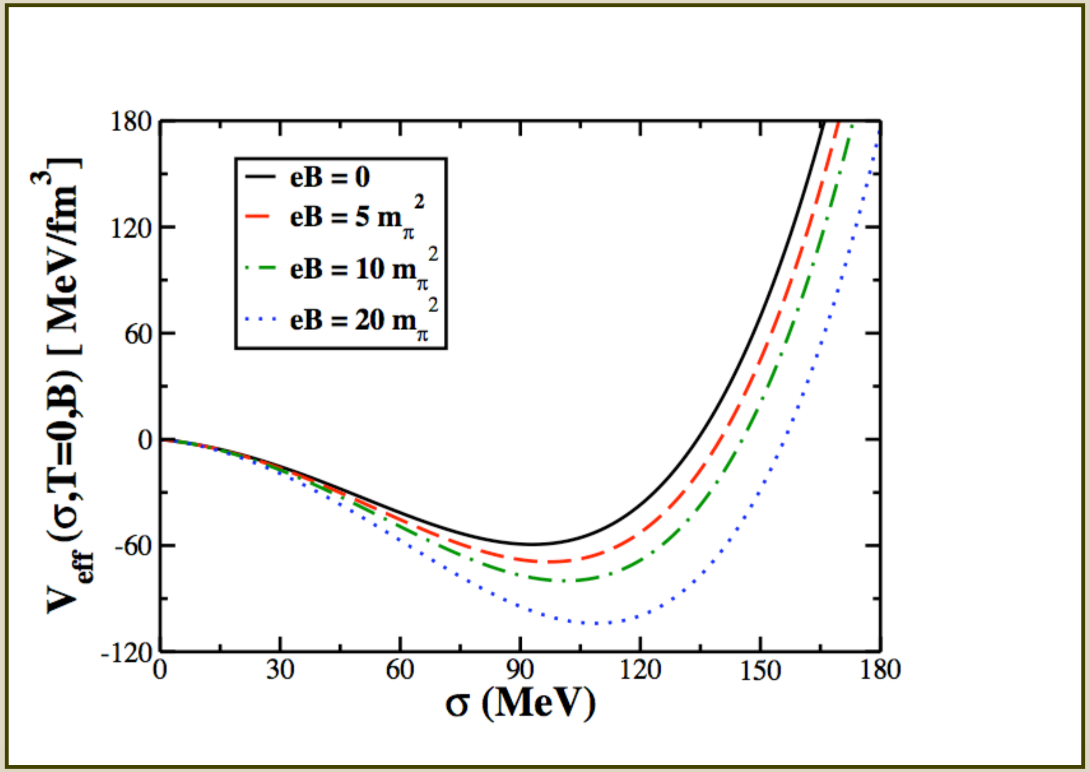
$\boxed{\vec{B} = B\hat{z}}$ $\xrightarrow{\text{choice of gauge}}$ $\boxed{A^\mu = (A^0, \vec{A}) = (0, -By, 0, 0)}$

$$\boxed{\begin{array}{l}(\partial^2 + m^2)\phi = 0 \\ \partial_\mu \to \partial_\mu + iqA_\mu\end{array}} \Rightarrow \boxed{p_{0n}^2 = p_z^2 + m^2 + (2n+1)|q|B}$$

$$\boxed{\begin{array}{l}(i\gamma^\mu\partial_\mu - m)\psi = 0 \\ \partial_\mu \to \partial_\mu + iqA_\mu\end{array}} \Rightarrow \boxed{p_{0n}^2 = p_z^2 + m^2 + (2n+1-\sigma)|q|B}$$

$\boxed{\sigma = \pm 1}$

Vacuum effective potential



Results in line with calculations in χPT and NJL, as in e.g.

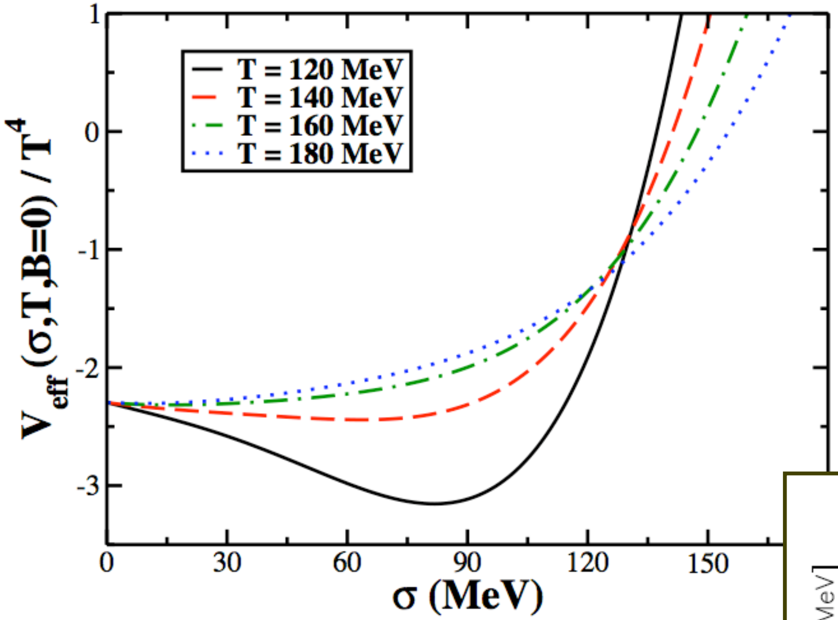
- Shushpanov & Smilga (1997)
- Cohen, McGady & Werbos (2007)
- Hiller, Osipov et al. (2007/2008)
- …

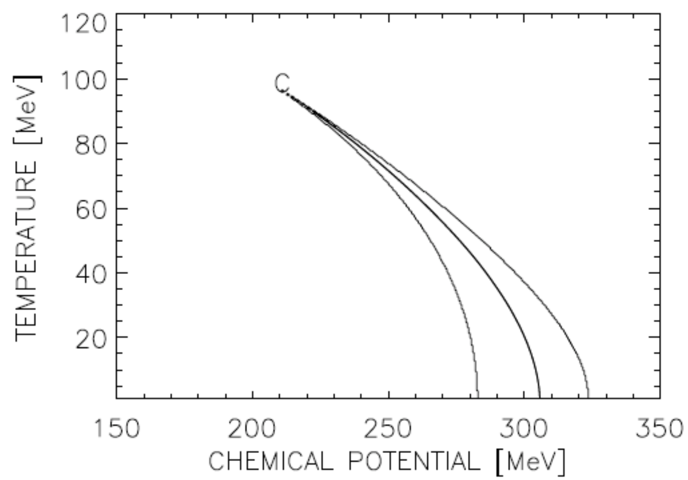
$$\boxed{m_\pi^2 \sim 10^{19} G}$$

- Condensate grows with increasing magnetic field
- Minimum deepens with increasing magnetic field
- Relevant effects for equilibrium thermodynamics and nonequilibrium process of phase conversion ?

Thermal corrections:

B = 0:

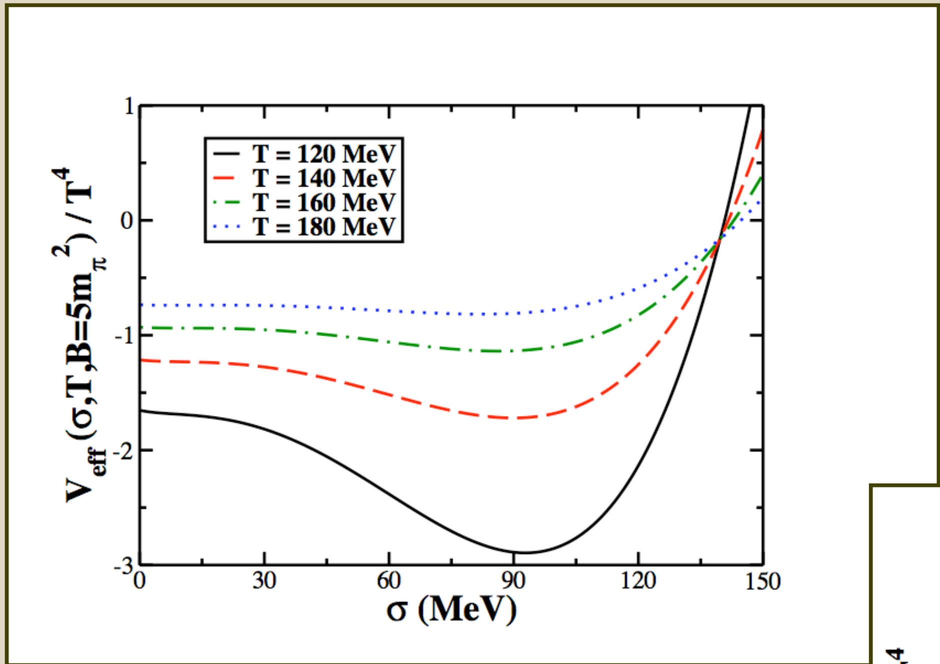




- A crossover at μ=0
- Critical temperature: $T_c \sim$ 140-150 MeV

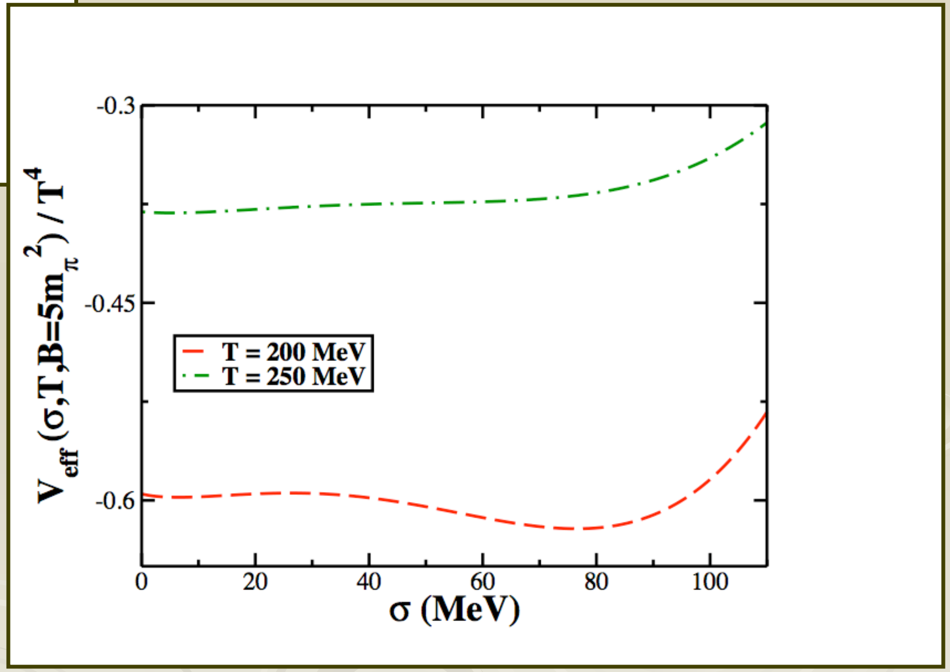
[Scavenius et al. (2001)]

$eB = 5\ m_\pi^2$:

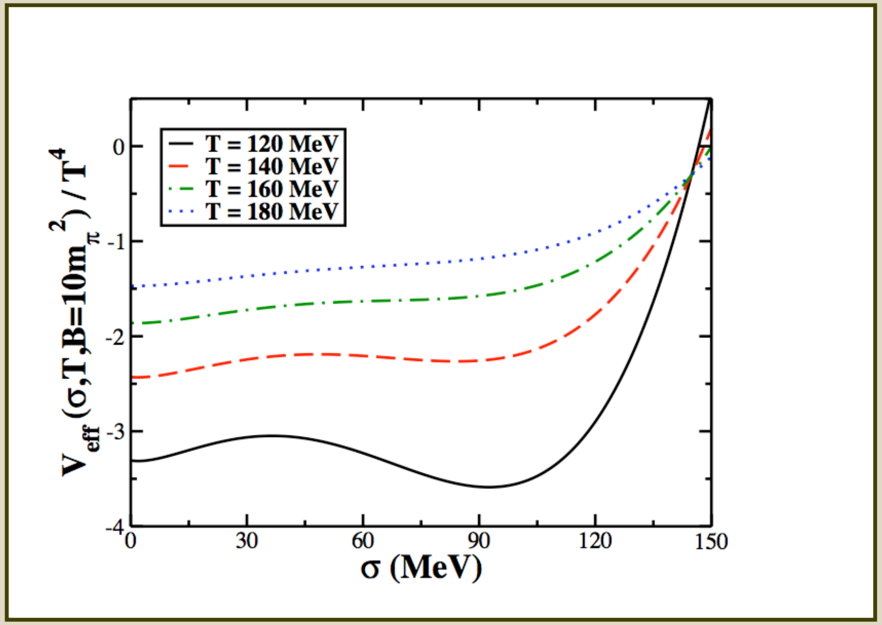


- Higher critical temperature: $T_c > 200$ MeV

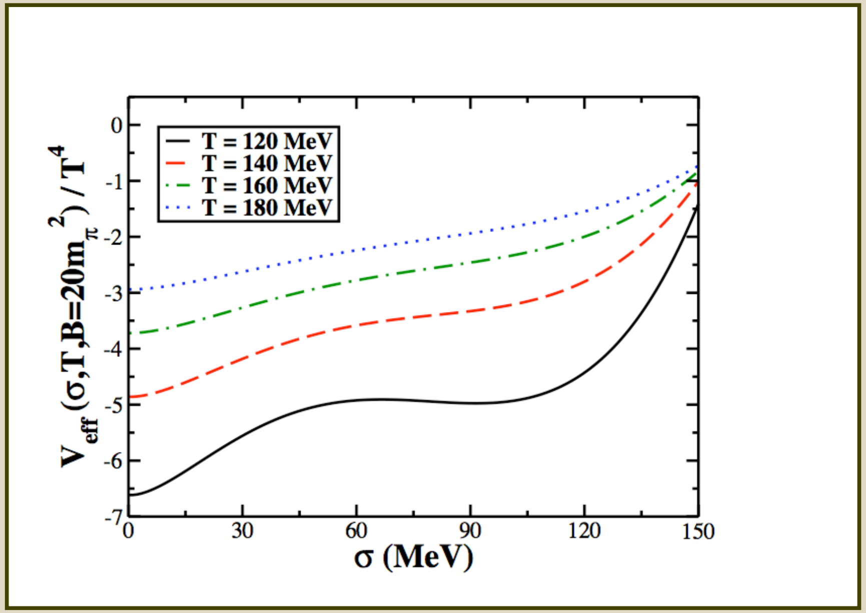
- Tiny barrier: very weakly 1st order chiral transition!



eB = 10 m_π^2:



eB = 20 m_π^2:



- Critical temperature goes down again due to the larger hot fermionic contribution (T_c < 140 MeV)
- Larger barrier: clear 1st order chiral transition!
- Non-trivial balance between T and B… one needs to explore the full phase diagram

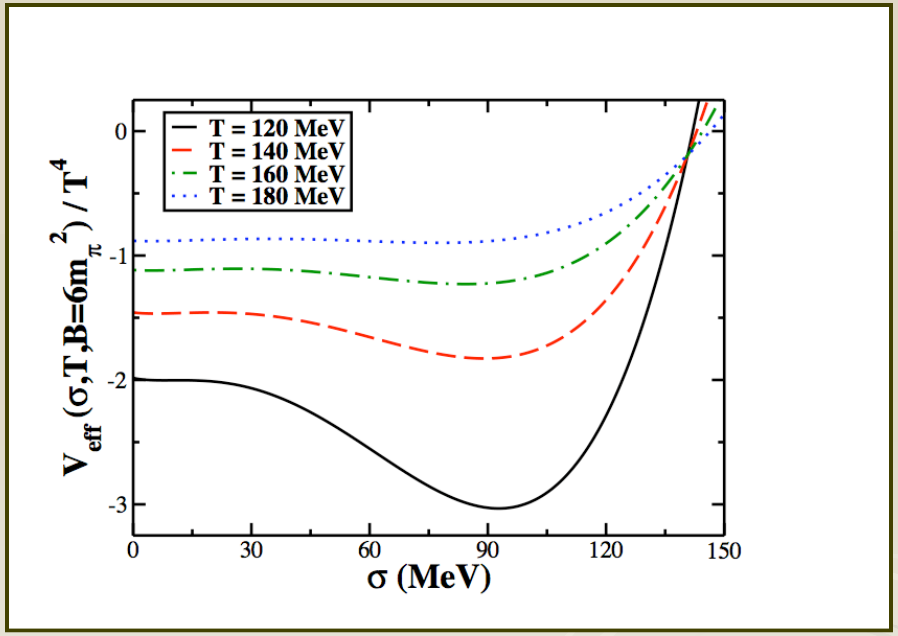
Some phenomenological consequences

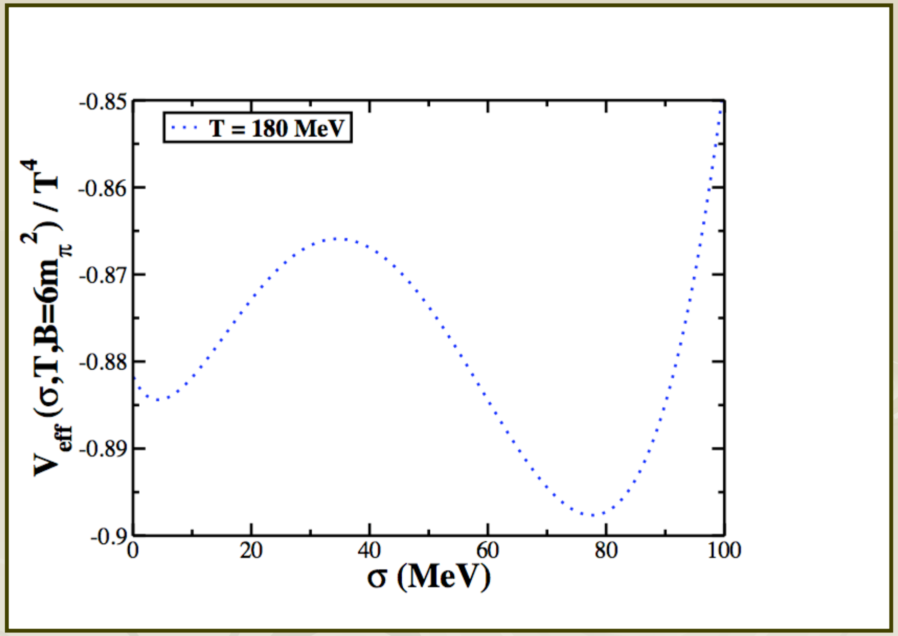
[Mizher & ESF (2008,2009)]

• At RHIC, estimates by Kharzeev, McLerran and Warringa (2008) give:

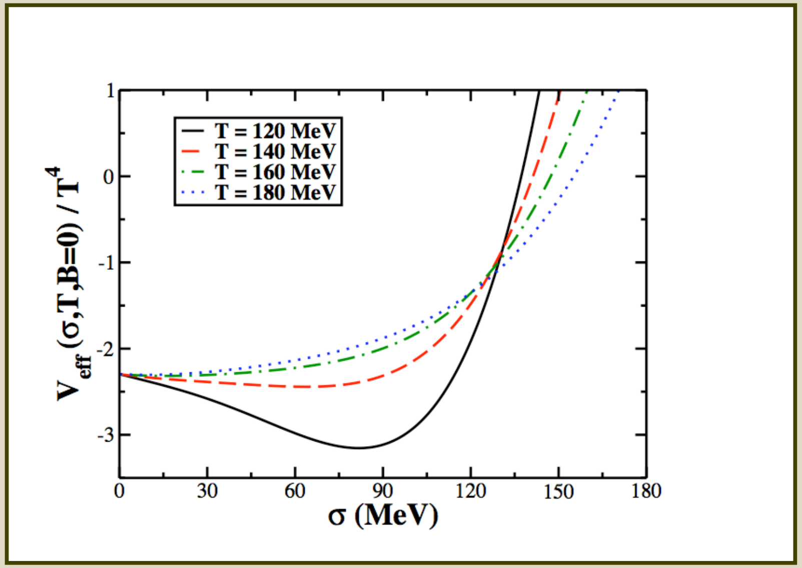
$$\boxed{eB \sim 5.3\ m_\pi^2}$$

• For LHC, we have a factor (Z_{Pb}/Z_{Au} = 82/79) and some small increase in the maximum value of eB due to the higher CM energy (as observed for RHIC). So, it is reasonable to consider $\boxed{eB \sim 6\ m_\pi^2}$



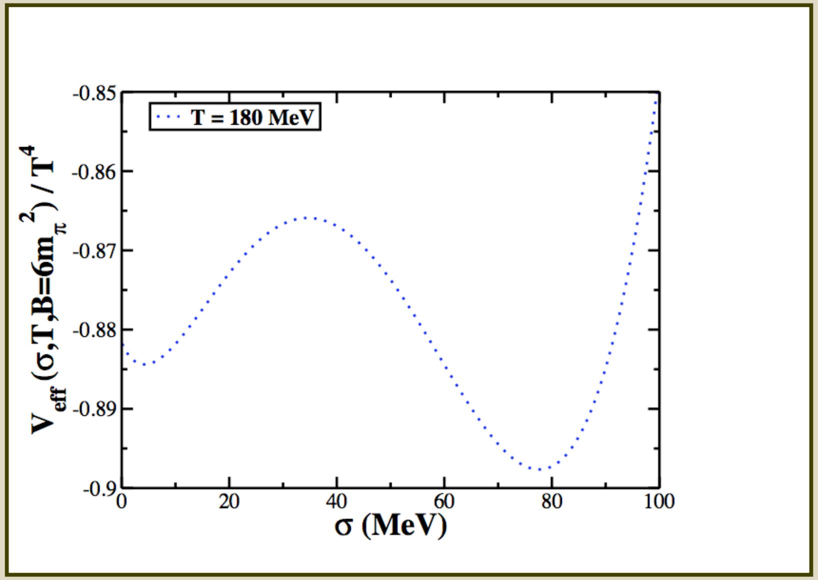


$B = 0$:



- Rapid crossover (no barrier)
- $T_c \sim 140$–150 MeV
- System "smoothly" drained to the true vacuum: no bubbles or spinodal instability

$eB = 6\, m_\pi^2$:



- Weak 1st order (tiny barrier)
- $T_c > 200$ MeV
- Part of the system kept in the false vacuum: some bubbles and spinodal instability, depending on the intensity of supercooling
- Explosive phase conversion ?

Remarks on magnetic field effects on the phase diagram of QCD

- Lattice QCD indicates a crossover instead of a 1st order chiral transition at $\mu=0$. A strong magnetic background can change this situation.

- For RHIC and LHC, the barrier in the effective potential seems to be quite small. Still, it can probably hold part of the system in a metastable state down to the spinodal. -> Different dynamics of phase conversion.

- B falls off rapidly at RHIC - early-time dynamics to be affected.

- Non-central heavy ion collisions might show features of a 1st order transition when contrasted to central collisions. However, then finite-size effects become important [Palhares, ESF & Kodama (2009)] (CPOD talk by L. Palhares).

- Caveat: treatment still admittedly very simple - in heavy ion collisions, B varies in space and time. It can, e.g., induce a strong electric field that could play a role [Cohen et al. (2007)].

Step 2: incorporating CP violating terms -> CP-odd LσM

[Mizher & ESF (2008,2009)]

- Following Pisarski & Wilczek (1984) and 't Hooft (1986) we describe the chiral mesonic sector (including the 't Hooft *det* term) by

$$\mathcal{L}_\chi = \frac{1}{2}\mathrm{Tr}(\partial_\mu\phi^\dagger\partial^\mu\phi) + \frac{a}{2}\mathrm{Tr}(\phi^\dagger\phi) - \frac{\lambda_1}{4}[\mathrm{Tr}(\phi^\dagger\phi)]^2 - \frac{\lambda_2}{4}\mathrm{Tr}[(\phi^\dagger\phi)^2] + \frac{c}{2}[e^{i\theta}\det(\phi) + e^{-i\theta}\det(\phi^\dagger)] + \mathrm{Tr}[h(\phi+\phi^\dagger)]$$

Expressing the chiral field as (N_f=2)

$$\phi = \frac{1}{\sqrt{2}}(\sigma + i\eta) + \frac{1}{\sqrt{2}}(\vec{a}_0 + i\vec{\pi})\cdot\vec{\tau}$$

the potential takes the form

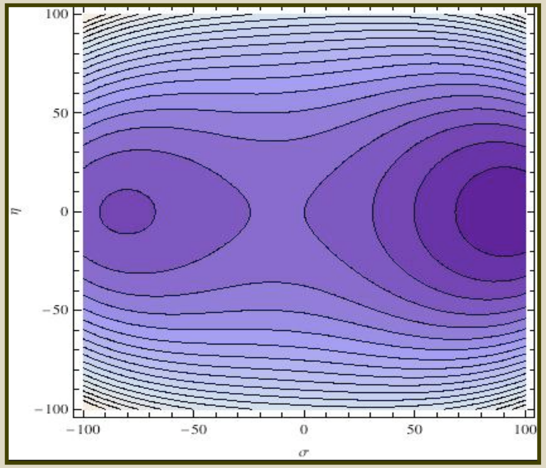
$$\begin{aligned} V_\chi \quad = \quad & -\frac{a}{2}(\sigma^2+\vec{\pi}^2+\eta^2+\vec{a}_0^2) \\ & -\frac{c}{2}\cos\theta\ (\sigma^2+\vec{\pi}^2-\eta^2-\vec{a}_0^2) + c\ \sin\theta\ (\sigma\eta - \vec{\pi}\cdot\vec{a}_0) - H\sigma \\ & +\frac{1}{4}(\lambda_1+\frac{\lambda_2}{2})(\sigma^2+\eta^2+\vec{\pi}^2+\vec{a}_0^2)^2 + \frac{2\lambda_2}{4}(\sigma\vec{a}_0+\eta\vec{\pi}+\vec{\pi}\times\vec{a}_0)^2 \end{aligned}$$

with $H=2^{1/2}h$ and the parameters fixed by vacuum properties of mesons (θ=0).

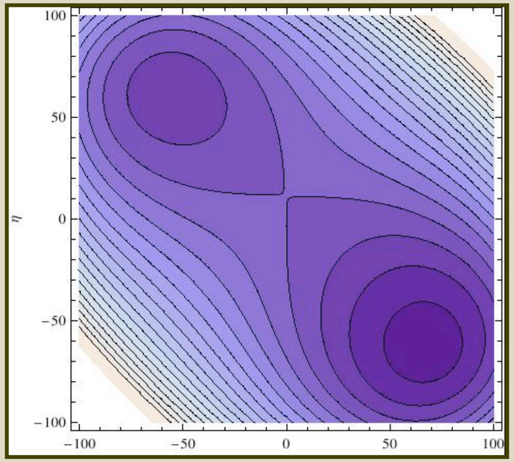
- Quarks are coupled to the chiral fields in the same fashion as before.

Contour plots for the effective potential [Mizher & ESF (2008,2009)]

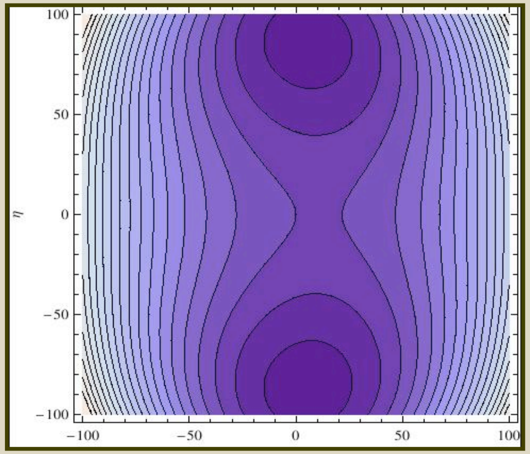
T=0:



$\theta=0$



$\theta=\pi/2$

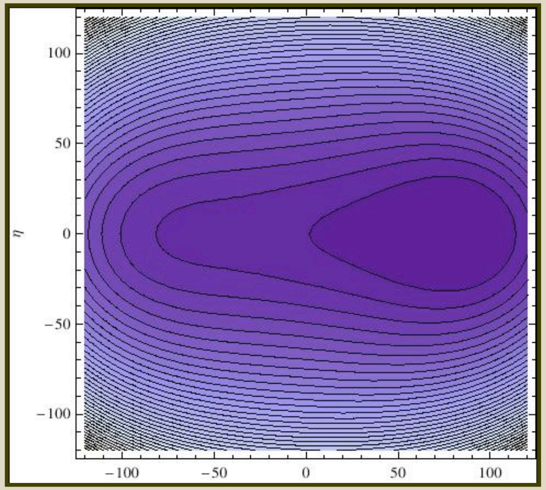


$\theta=\pi$

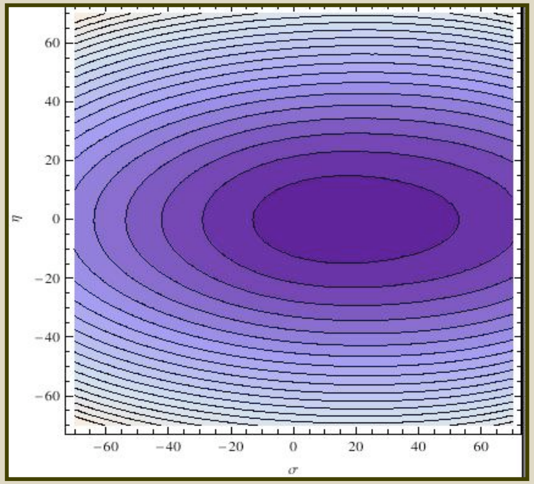
Increasing θ the positions of the minima rotate. For $\theta=\pi$ the global minimum is almost in the η direction (nonzero quark masses).

T > 0 , θ=0:

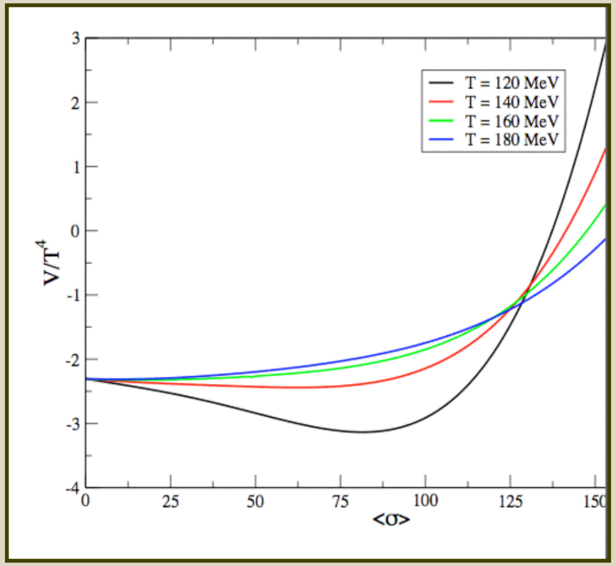
Keeping θ=0 the model reproduces the features of the usual LσM



T=120 MeV



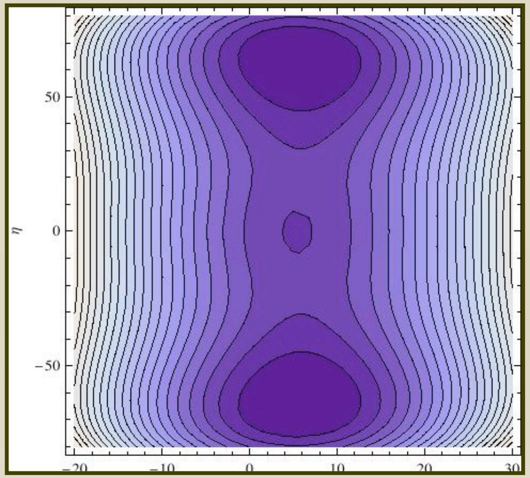
T=160 MeV



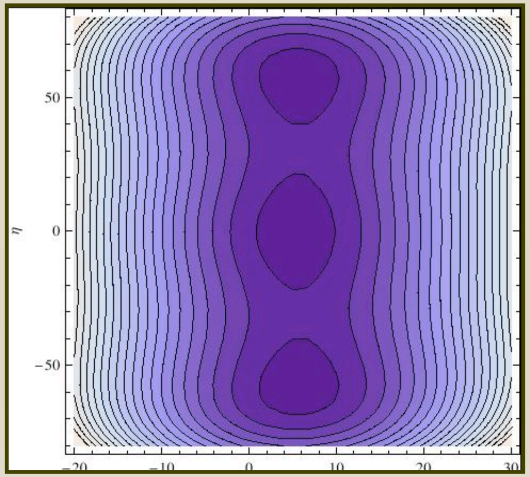
V *vs.* σ for several temperatures

$T > 0$, $\theta=\pi$:

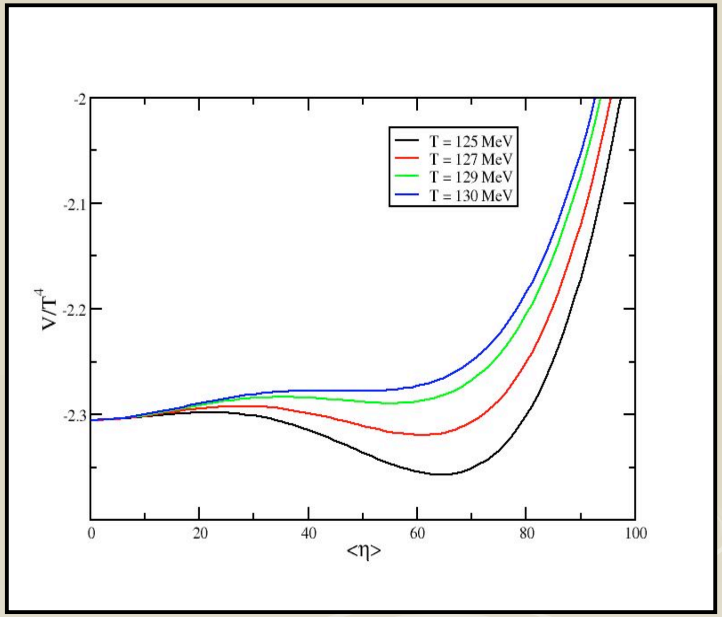
- Minima are almost in the η direction.
- As the temperature raises a new minimum appears at $\eta=0$, separated by a barrier, signaling a first-order transition.
- The critical temperatures for melting the two condensates are different, so that three phases are allowed.



T=125 MeV

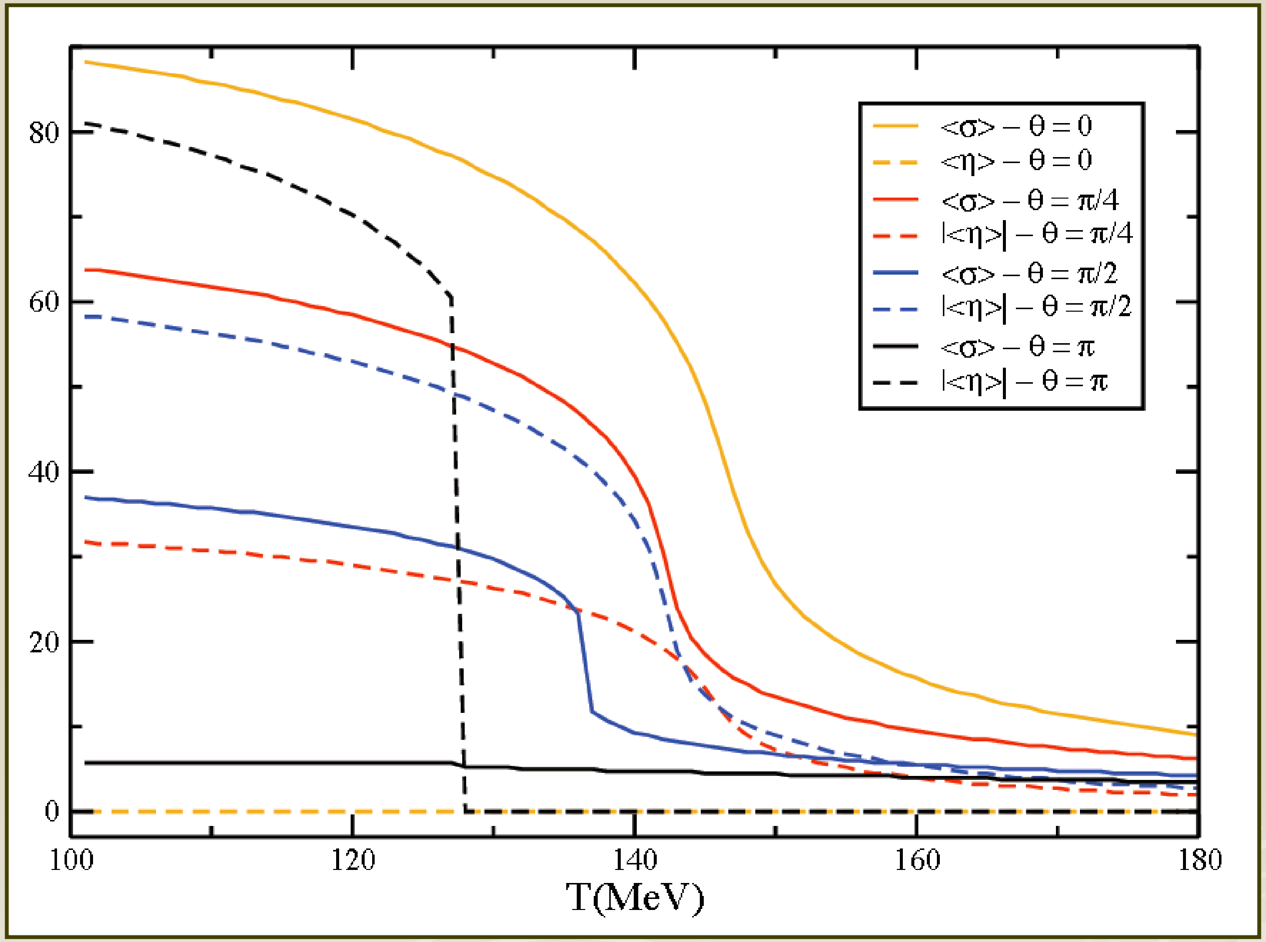


T=128 MeV



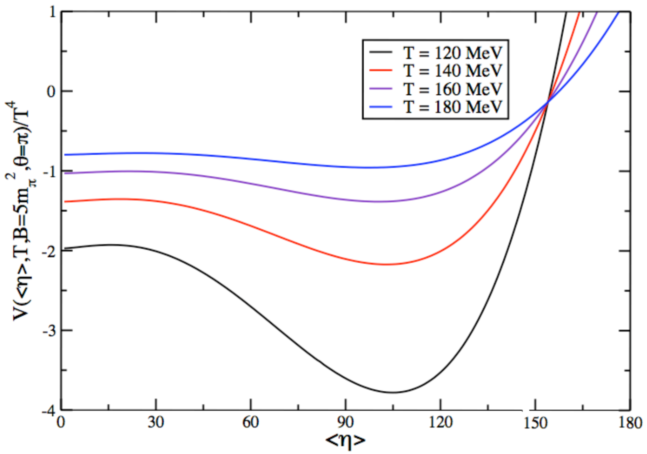
V *vs.* η for several temperatures around the transition.

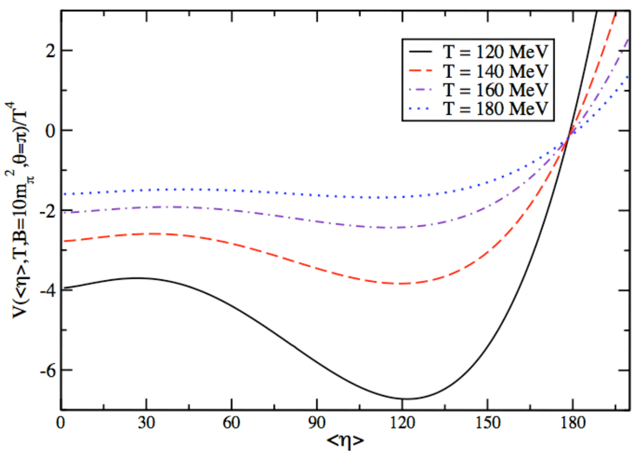
Condensates:



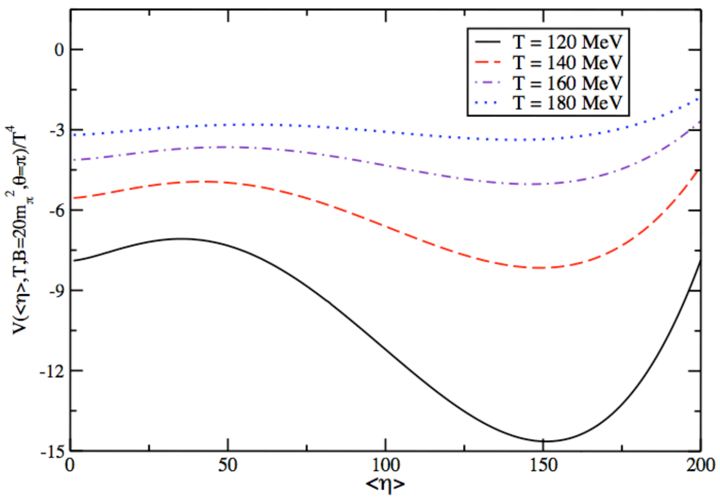
Adding a strong magnetic background (following the previous steps)

[Mizher & ESF (2008,2009)]





- T_c & the barrier become higher -> stronger first-order transition
- Effects on σ are the same as before



Remarks on the inclusion of a CP-violating term

• For nonzero θ, metastable CP-violating states appear quite naturally in the CP-odd LσM. However, this was not found in an extension of the NJL model [Boer & Boomsma (2008)].

• Larger values of θ tend to produce a 1st order chiral transition and might lead to the formation of domains (bubbles) in the plasma that exhibit CP violation. This reinforces the scenario of possible metastable CP-odd states in QCD, relevant for the chiral magnetic effect [Kharzeev et al (2008,2009)].

• This behavior is enhanced by the presence of a strong magnetic field, so that both effects seem to push in the same direction.

Discussion: a few questions to experimentalists & lattice people

• Strong magnetic fields can modify the nature of the chiral (and the deconfining) transition(s), opening new possibilities in the study of the phase diagram of QCD. It is also essential for charge asymmetry due to sphaleron transitions. How strong can one make B at RHIC ? How long lived ? How "uniform" ? By which experimental tricks ?

• An accurate centrality dependence study seems to be necessary, and finite-size effects are sizable for non-central collisions [talk by L. Palhares]. How thin can one bin in centrality and control finite-size effects (constrained by statistics) ?

• For theory, one needs to perform dynamical investigations to determine the relevant time scales and see if effects from CP-odd domains survive.

• One can compute the behavior of critical quantities as functions of B in effective models. How hard is it to do it on the lattice ? Any "sign problem" ? (a few things on the way [Chernodub et al.]).

To do list:

- More realistic treatment of the effective model, including confinement effects [work in progress with A.J. Mizher, M. Chernodub & K. Fukushima]

- Investigation of the low magnetic field regime at finite T, for $B < T$ and $B \sim T$ - full phase diagram

- Simulation of time evolution of the phase conversion process to compare relevant time scales to those in the crossover picture

- Possible signatures of these features in heavy ion collisions?

- Application to the primordial QCD transition [work in progress with A.J. Mizher]

- Situation at high density and applications to compact stars: phase structure inside *magnetars*